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Title

Pre-binding prior to full engagement improves loading conditions for front row players in contested rugby union scrums

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ABSTRACT

We investigated the effect of a *'PreBind'* engagement protocol on the biomechanics of contested Rugby Union scrummaging at different playing levels. *'PreBind'* requires front-row props to take a bind on opposing players prior to the engagement, and to maintain the bind throughout the scrum duration.

Twenty-seven teams from five different playing levels performed live scrums under realistic conditions. Video analysis, pressures sensors, and inertial measurement units measured biomechanical outcomes as teams scrummaged following different engagement protocols: the *CTPE* (referee calls 'crouch-touch-pause-engage'); the *CTS* ('crouch-touch-set'); and, the *PreBind* ('crouch-bind-set') variants.

PreBind reduced the set-up distance between the packs (-27%), and the speed at which they came into contact by more than 20%. The peak biomechanical stresses acting on front rows during the engagement phase were decreased in *PreBind* by 14-25% with respect to *CTPE* and *CTS*, without reducing the capability to generate force in the subsequent sustained push. No relevant main effects were recorded for playing level due to within-group variability and there were no interaction effects between playing level and engagement protocol.

Pre-binding reduced many mechanical quantities that have been indicated as possible factors for chronic and acute injury, and may lead to safer engagement conditions without affecting subsequent performance.

INTRODUCTION

Over the last years, scrummaging in rugby union has been the object of a lively debate focussed on player safety and injury prevention (Trewartha *et al.*, 2014). The biomechanical demands the forward players are subjected to while scrummaging have been described as being very intense (Cazzola *et al.*, 2015b; Du Toit *et al.*, 2004; Milburn, 1990; Preatoni *et al.*, 2013; Preatoni *et al.*, 2014; Quarrie & Wilson, 2000) and close to what studies on cadaveric specimens and computational models have identified as potentially hazardous for spinal damage (Nightingale *et al.*, 1997; Przybyla *et al.*, 2007; Tchako & Sadegh, 2009; Winkelstein & Myers, 1997). Epidemiological evidence has highlighted only a moderate prevalence of scrum-related acute injuries (approximately 8% of all rugby union injuries) (Brooks *et al.*, 2005; Fuller *et al.*, 2008; Fuller *et al.*, 2009; Targett, 1998; Trewartha *et al.*, 2014; Williams *et al.*, 2013). However, the scrum has been associated with about 40% of the injuries causing irreparable damage, primarily due to spinal cord injuries (Brown *et al.*, 2013; Fuller, 2008; Quarrie *et al.*, 2002; Trewartha *et al.*, 2014). Also, the scrum has been determined to have a comparatively high injury risk per event (Fuller *et al.*, 2007; Roberts *et al.*, 2014; Taylor *et al.*, 2014). Starting from this scenario and from the consideration that the scrum is a relatively controllable part of the game (Trewartha *et al.*, 2014), *World Rugby* (previously known as the *International Rugby Board*) initiated a research programme to assess current practices and explore changes in the laws that could improve players' safety. As a result, in 2012-13 and 2013-14 *World Rugby* trialled two amendments of the "Scrum" Law (World Rugby, 2015a), starting from the rules in use until the 2011-12 (Northern Hemisphere) competition season (Table 1). The 2013-14 amendments were eventually approved in November 2014 and are now fully integrated in the laws of the game (Law 20, World Rugby (2015b)).

The trialled changes were informed by the *Biomechanics of the Rugby Scrum* project conducted at the University of Bath (UK). The studies published to date have analysed forces and motions in machine (Preatoni *et al.*, 2013; Preatoni *et al.*, 2014) and live scrummaging

(Cazzola *et al.*, 2015b), and have shown that de-emphasising the initial engagement could lead to significant reductions in the biomechanical stresses experienced by players in a scrum. These studies have included multiple scrummaging procedures and teams, but have not demonstrated yet whether the introduction of a pre-bind procedure (2013-14) could be effective in live contested scrummaging under realistic conditions with teams from any playing level, ranging from senior international to amateur levels.

Therefore, the aim of this study was to assess (1) whether establishing a pre-bind between opposing packs prior to full scrum engagement, which is subsequently maintained, could affect the loading and stability characteristics of live scrummaging, and (2) whether any change transfers across the spectrum of rugby playing levels. Our hypothesis was that the introduction of a pre-binding scrummaging procedure that reduces the dynamics of the initial engagement could lower the biomechanical stresses on forwards and improve the stability of the scrum at any playing level included in the analysis.

**** Table 1 near here ****

MATERIALS AND METHODS

Study design

A cross-sectional study was carried out to assess the changes in multiple biomechanical measures (dependent variables) collected during scrum events as an effect of two independent variables, playing level (between-group) and scrum engagement protocol (within-group).

Participants

Twenty-seven rugby teams (i.e. 2 packs per team, equalling a total of 54 forward packs, 432 players) were recruited and volunteered to participate in the study. Each team (i.e. pair of forward packs) was assigned to one of five playing levels depending on their competitive playing level (Table 2). Recruitment to the study was initiated by written contact to establish potential interest in participation, either via a national governing body representative / competition coordinator as gatekeeper or via direct contact with the teams' Director of Rugby. Table 2 specifies the competitions searched to recruit teams to each category, the final sample of 27 teams arose from a pool of approximately 136 teams initially contacted. The Institutional Ethics Committee of the University of Bath approved the research, and every participant provided written informed consent before participation.

**** Table 2 near here ****

Data Collection

Testing was devised and carried out with the aim of replicating match conditions as realistically as possible to enhance ecological validity. A fully portable and minimally obtrusive system was assembled at the venue where the participant team regularly trained. Measures were collected from real contested scrums performed on natural turf. To prepare for the scrummaging session, all players undertook a coach directed warm-up involving running, agility and scrum-specific drills. Prior to testing, the packs also performed some practice attempts following the scrum procedures under investigation, to reduce the risk of learning effects on the collected measures.

During the testing session, each team was asked to perform one set of 4 suitable scrums for each of the 3 engagement protocols, which had been defined by a steering group within *World Rugby* (Table 1) (Cazzola *et al.*, 2015b). The order of engagement conditions was randomly presented across teams, but all teams performed the trials in a blocked fashion. A recovery of at least 1 min between trials and 5 min between sets was allowed to avoid fatigue. When re-sets were needed, due to anticipation of the engagement call or to scrum disruptions, teams were required to repeat the trial. However, an overall maximum of 16 scrums was performed.

The two packs scrummaging were named A and B. Pack A had possession and put-in to the scrum for all scrums in the session. The ball throw in was performed by a scrum half lying on the ground (to avoid video occlusion) after the two packs had come into contact and established a stable contest. Both warm-up and test trials were supervised by a qualified coach, who carefully double-checked that scrums were carried out in respect of the rules. Players were aware of the broader aims of the project, but not of the specific aspects or quantities taken into consideration to characterise scrum changes.

Instrumentation and Data Processing

A control system (cRIO-9024 programmed in Labview v2010, National Instruments, USA) triggered and time-synchronised all the measuring devices and controlled the playback of the referee's calls via pre-recorded audio files with consistent timing between vocal commands (Table 1).

Two thin-film pressure mats (#3005E Versatek XL, Tekscan Inc, USA), previously calibrated (Cazzola *et al.*, 2014) and trimmed to fit into bespoke protective sleeves, were attached onto the two shoulders of each front-row player in Pack A. The signals from the six pressure transducers were collected at 500 Hz through two F-Scan systems (Tekscan Inc, USA) and were used to estimate the forces (normal to the sensor surface) exchanged between the two packs (Cazzola *et al.*, 2015b; Cazzola *et al.*, 2014). The overall force between the two front rows and measured on Pack A ($F_{front\text{-}row}$) was calculated as the sum of the individual forces from the three players wearing pressure sensors.

An Inertial Measurement Unit (MTw, Xsens Technology BV, NL) was secured in a plastic holder, attached onto the estimated position of the C7 vertebra of the six front-row players and used to measure three-dimensional accelerations of the upper trunk during the engagement. The raw acceleration signal was sampled at 1800 Hz and then transmitted at 50 Hz through the proprietary strap-down integration method (Xsens Technology BV, NL). The resultant of C7 tri-axial accelerations was used as a measure of impact loading to compare engagement conditions.

Two-dimensional players' kinematics was recorded from three different views. Two cameras operating at 200 Hz and 50 Hz (HVR-Z5, Sony, Japan) were positioned at a height of ~8 m above the centre of the scrum and captured the teams' transverse motion. Another two cameras (HDR-HC9, Sony, Japan) operating at 50 Hz were placed on the left and right side of the scrum at a distance of 18 m from the centre and recorded the teams' motion in the sagittal plane. The field of view of every camera was optimised by zooming-in as much as possible but allowing the entire scrum to be imaged throughout the action. Multiple two-dimensional calibrations using 4-point projective scaling were carried out by means of a three-dimensional calibration object. Manual digitising (Vicon Motus V9, Vicon Motion Systems, USA) was used to identify the location of selected body landmarks and to allow the estimation of a set of kinematic variables (Figure 1 and Table 3-5). Previously published research had demonstrated a good level of reliability for the variables under analysis (Preatoni *et al.*, 2012).

Custom-made functions were written in Matlab (R2011b, The MathWorks Inc, USA) to process data and extract the variables of interest from each scrummaging trial. The set of analysed measures (Table 3-5) was selected with the intent to best depict the kinematics and kinetics of contested scrummaging across all phases of the event (Cazzola *et al.*, 2015b), from the 'Approach' (APRC, i.e. from initial set-up at the onset of movement to the first contact between forward packs), through the 'Engagement' (ENG, i.e. from the first contact to 1 s after the peak of contact forces), to the 'Sustained Push' (SPSH, i.e. an interval of 1 s after the end of the Engagement interval). Measures of interest included variables related to the whole scrum (i.e. time of onset of movement, compression force, contact speed), to the front row players (i.e. average peak acceleration during the engagement), or to specific positions such the loose-head or tight-head prop (i.e. hip-shoulder offset, hip angle). Video footage was also inspected to count the number of unsuccessful scrum outcomes (scrum disruptions) over the total number of successful attempts. Early stage disruptions were defined as occurring during the engagement phase.

Statistics

Average measures from individual teams were pooled and used to describe playing level and engagement protocols through descriptive statistics. Mixed design analysis of variance (ANOVA) was performed to test the significance ($p<0.05$) of main effects (playing level and engagement protocol), and the possible interaction between the two factors. Bonferroni tests were applied in the post-hoc analysis. Effect sizes were reported as eta-squared (η^2).

RESULTS

No interaction effect between playing level and engagement protocol was found for any of the analysed measures. Therefore, results will be presented by focussing on the two main effects separately and going through the three main phases of scrummaging sequentially.

Approach to contact

PreBind reduced the front row distance at set up and the anticipation of the onset of movement by an average of 0.13 m ($p=0.001$, $\eta^2=0.672$) and 0.13 s ($p=0.001$, $\eta^2=0.221$), respectively (Table 3). No major differences in the time of onset were recorded between playing levels, whereas the community level teams tended to set up with a larger gap between the two front rows (Table 3) than the other categories ($p=0.010$; $\eta^2=0.342$). Front row props assumed a more "shoulder above hips" position in *PreBind* than in the other conditions when setting up prior to the engagement (Table 3). Indeed, *PreBind* showed higher values of this measure for the loose-head and the tight-head props ($p<0.001$; $\eta^2=0.325$ for both playing positions).

Engagement (initial contact to 1 s after the peak of compression force)

PreBind significantly decreased all the measures of force and acceleration used to gauge the intensity of the impact between the two packs (Table 4). Peak force in *PreBind* was 25% lower than in *CTPE* and 24% than in *CTS* ($p<0.001$; $\eta^2=0.447$). Average peak acceleration ($p<0.001$; $\eta^2=0.528$) and maximum peak acceleration across the six front-row players ($p<0.001$; $\eta^2=0.386$) were, respectively, 18% and 14% less than in CTPE and 17% and 14% less than in CTS. *PreBind* also reduced the loss of force (drop in force from peak to minimum value following the peak) during the "rebound" phase (Cazzola *et al.*, 2015b; Preatoni *et al.*, 2014) by 31% with respect to the other two conditions. No main effects for playing level were detected in any of these four variables.

Front row props showed a decreased hip range of motion in *PreBind* in comparison with *CTPE* and *CTS* ($p<0.001$, $\eta^2=0.181$ and 0.314 for the loose- and tight-head side, respectively), but no major differences across playing levels (Women had higher hip range of motion than University teams). The adoption of *PreBind* also lowered the vertical excursion of the props' shoulders ($p=0.003$, $\eta^2=0.122$ for loose-head; $p<0.001$, $\eta^2=0.174$ for tight-head), and the variability of all props' centre of mass motion during the engagement phase. Indeed, the area of the confidence ellipse enclosing 95% of centre of mass excursions was between ~25% (loose-head, *CTS* vs. *PreBind*) and ~41% (tight-head, *CTPE* vs. *PreBind*) less in *PreBind* than in the other conditions. No main effects for playing level was found for these last variables either, with the exception of a larger ellipse area for Women vs. International teams for the tight-head props.

Sustained Push (end of engagement to 1 s after the end of engagement)

No significant differences and small effect sizes were found in the average force exerted during the sustained push as a factor of either engagement protocol or playing level. The magnitude of force between packs over the sustained push ranged from 2.6 kN (Women, *CTPE*) and 4.4 kN (Elite, *CTPE*). On average, Elite and International teams achieved a sustained push about 28% larger than Women and about 20% bigger than University and Community, but within-group variability was relatively high in these measures.

Changes in players' posture during the sustained push did not highlight consistent patterns across either engagement protocol or playing levels, with the exception of the Women teams, who showed a tendency for higher 'shoulder above the hips' distance, but only significant in comparison with the Elite and University groups ($p=0.005$, $\eta^2=0.279$ for loose-head; $p=0.039$, $\eta^2=0.197$ for tight-head).

Scrum outcome

A total of 297 scrums were analysed as part of the study. An average of 3.7 (standard deviation of 1.0) successful trials per condition per team was collected. The highest number of scrum disruptions occurred in *CTS* trials (23%), followed by *CTPE* (15%) and *PreBind* (12%). Early stage collapses were 6%, 12% and 6% for *CTPE*, *CTS* and *PreBind*, respectively. The number of instances of front rows “popping up” out of the scrum during the sustained push phase was low, but slightly higher in *PreBind* (3%) compared with *CTPE* (1%) and *CTS* (0%).

DISCUSSION

The primary objectives of this study were to assess whether (1) the modifications introduced in the scrummaging procedures since 2011-12 could reduce the biomechanical loads that players are subjected to during a live contested scrum, and (2) whether any reduction would occur irrespective of the playing level studied. A secondary objective was to identify whether the engagement protocols subsequently trialled in the 2012-13 and 2013-14 seasons (Table 1) could also enhance the stability of the scrum during the engagement phase. Our results showed that the introduction of a pre-bind procedure (World Rugby, 2015a; World Rugby, 2015b) significantly decreased all the measured indicators of mechanical stress on front-row players and improved the measures used to assess scrum stability, irrespective of playing level. This is a fundamental follow-up to previously published findings about machine scrummaging (Preatoni *et al.*, 2013; Preatoni *et al.*, 2014) and live scrummaging in elite teams only (Cazzola *et al.*, 2015b). Although injury risk was not directly assessed, our work shows that maintaining the bind throughout the engagement may potentially reduce the injury factors related to the dynamics of the impact, and that this alteration benefits rugby forwards at any competition level.

The use of a de-emphasised engagement (*PreBind*) led to (i) a significant reduction of the distance at which the two packs set-up, (ii) a decreased closing speed at which the scrum was engaged, and (iii) less anticipation of the referee’s call, across all Rugby Union competition levels. These outcomes, which reinforce previous findings from machine (Preatoni *et al.*, 2013; Preatoni *et al.*, 2014) and elite contested scrummaging (Cazzola *et al.*, 2015b), support the hypothesis that the *PreBind* engagement imposes a change in scrummaging behaviour, whereby forward packs at any playing level tend to reduce the focus on gaining advantage through the initial impact.

The reduction in the engagement dynamics took the form of a substantial reduction in all the mechanical measures (peak forces, peak accelerations) that studies related to impacts at spinal level have indicated as determinants of acute and/or chronic injury and pain (Dennison *et al.*, 2012; Kuster *et al.*, 2012; Trewartha *et al.*, 2014). In line with our previous findings on elite teams (Cazzola *et al.*, 2015b) and with research from other sports studying the relation between collisions and closing distances (Ocwieja *et al.*, 2012), peak impact forces and accelerations across the two front rows were on average lowered by between 14% and 25%, without this being detrimental for the achievement of an equally effective sustained push. Indeed, the change in the engagement procedure did not lead to any alteration in the magnitude of sustained push force. This observation further confirms the assumption (Cazzola *et al.*, 2015b; Preatoni *et al.*, 2014) that achieving a high initial contact force is not necessarily functional or essential for the sustained push, which is when the contest for the ball possession should begin. The introduction of the pre-bind between props mitigated the loss of force generation capability over the interval between the initial impact and the establishment of the sustained push, therefore further encouraging the consistent application of forces without rapid changes.

In previous studies on machine scrummaging (Preatoni *et al.*, 2013; Preatoni *et al.*, 2014) we observed that reducing the dynamics of the initial engagement significantly decreased shear forces and fluctuations in compression force. We hypothesized that such a change could improve the stability of the scrum in the first seconds of its formation, but we also remarked the need to analyse a live contested situation, because those effects could be influenced by the static opposition provided by the scrum machine. Some kinematic outcomes from the current study appear to validate our original interpretation. In comparison with *PreBind*, *CTPE* and *CTS* tended to show higher ranges of hip motion, larger excursion of the shoulders in the vertical direction and significantly bigger variability of centre-of-mass motion in the sagittal plane for both the loose-head and the tight-head props. All these measures provide an indirect index of scrum stability as their increase would indicate a larger amount of fluctuation at the interface between the packs, which is an environment characterised by very high forces and multiple interactions between individuals exerting maximum effort. The *PreBind* protocol may therefore help in creating a safer bind across the opposing props and hence in controlling body posture during the engagement process, since a downward inclination of the trunk may cause loss of balance (Cazzola *et al.*, 2015b). The count of scrum resets, lower for *PreBind*, and the analysis of props' 'shoulder above hips' position, higher for *PreBind*, seem to corroborate this conclusion although large-scale data from actual matches are still to be carried out. The *PreBind* engagement procedure was formally adopted into law by *World Rugby* (World Rugby, 2015b) for continued implementation globally at all playing levels (World Rugby, 2015a). Initial epidemiology data carried out after the local introduction of South African Rugby Union modified amateur scrum laws (Hendricks *et al.*, 2014) in combination with the new engagement law have reported a reduction of the catastrophic injury occurrences related to scrum events, especially with regards to those due to 'impact on engagement', (Viljoen W, "personal communication") and therefore seem to corroborate our findings.

In conclusion, the results from this research supported the adoption of the *PreBind* protocol as a valid solution to be used at all playing levels to reduce the mechanical stresses acting on rugby forwards during the engagement of a scrum and to create a more stable condition for the ball contest to take place. The combination of reduced forces and improved stability should generate safer scrummaging conditions and in the long term has the potential to lead to a reduction in both acute and chronic injury occurrence. However, it is important to underline that such a conclusion is speculative, since this study assessed the biomechanics of scrummaging but did not measure injury risk or how external loads and body motions could translate into local injurious stresses on anatomical structures.

In this study, two scrum packs from the same team were paired. This choice was imposed by both confidentiality (i.e. disclosure of performance-related data of one team to potential competitors) and organisational (i.e. making the two teams meet on the same training ground) needs, and could have limited the ecological validity of the protocol. Another limitation of the research was dictated by the search for the best compromise between reliability of measures and ecological validity: pressure sensors represented the only available solution for unobtrusively estimating the forces exchanged between the two packs. However, the pads used covered only the shoulder area and may have underestimated the area of contact between the two front rows (e.g. by neglecting the contribution of the head). Moreover, pressure sensors only measure the component of force that is perpendicular to the contact surface and therefore the shear forces acting between players' shoulders cannot be measured.

PERSPECTIVES

This study closes a cycle of investigations about the influence of scrum engagement procedures and playing level on the biomechanical demands acting on rugby union forwards, and hence on the influence that a change in the engagement procedures can have for acute and chronic pain and for acute or overuse injuries. The analysis we carried out indicated the introduction of a pre-bind procedure as a possible valid strategy to generate safer scrummaging conditions, the effects of which will be verified when epidemiological results become available.

The findings we report had a worldwide impact in the area of sports governance and sports medicine. They guided the introduction of law amendments and the trialling of those with a view to promote players' welfare. Also, they may inform scientists, physicians and practitioners working in sports involving contact events, in terms of promoting safer practice, better understanding of injury mechanisms, and designing ad-hoc strength and conditioning activities for the players.

Further research is needed to identify the mechanisms that link external loads and motion of anatomical segments (i.e. cervical and lumbar spine) to the conditions and thresholds for structural damage. Such a challenging objective could be tackled through an integrated analysis (Preatoni *et al.*, 2015) that combines in-vivo testing (Cazzola *et al.*, 2015b; Cazzola *et al.*, 2015c; Preatoni *et al.*, 2014) with computer simulation (Cazzola *et al.*, 2015a) and finite element models (Holsgrove *et al.*, 2014).

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TABLES

Table 1. Description of the engagement conditions

Condition:	'Crouch, Touch, Pause, Engage' (*CTPE*) – baseline condition
Timing of referee's calls:	Crouch (t= -5.2 s) ; Touch (t= -2.9 s) ; Pause (t= -1.2 s) ; Engage (t= 0.0 s)
Season(s) (years):	Between 2007-08 and 2011-12
Full Description:	Following an engagement call sequence of 'crouch-touch-pause-engage' the forward packs engaged with each other and held a short-duration sustained push. This condition was regarded as the baseline condition for data analysis as it represented scrummaging practice and law at the inception of the research project.
Condition:	'Crouch, Touch, Set' (*CTS*)
Timing of referee's calls:	Crouch (t= -4.0 s) ; Touch (t= -1.7 s) ; Set (t= 0.0 s)
Season(s) (years):	2012-13
Full Description:	The forward packs set up as in *CTPE*. Following an engagement call sequence of "crouch-touch-set" the forward packs engaged with each other and held a short-duration sustained push. The vocal commands removed the "pause" so that this was non-verbal and the final command was changed from "engage" to "set" to reflect the scrum law amendment trials introduced globally by the IRB from September 2012.
Condition:	'Crouch, Bind, Set' (*PreBind*)
Timing of referee's calls:	Crouch (t= -4.0 s) ; Bind (t= -1.7 s) ; Set (t= 0.0 s)
Season(s) (years):	2013-14
Full Description:	The forward packs set up according to their normal practice in terms of within-pack binding and body positions but reduced their spacing sufficient to allow the subsequent actions whilst maintaining balance. The scrum followed an engagement call sequence of 'crouch-bind-set'. On the 'crouch' players moved into their normal crouched posture. On 'bind' all four props moved their outside arms forward to take a bind on their opposition's body past the point of their shoulder. The LH props moved their left arm inside the right arm of the TH and gripped the TH prop's jersey on the back or side. The TH props moved their right arm outside the left upper arm of the opposing LH prop and gripped the LH prop's jersey with the right hand only on the back or side. The props were instructed not to grip the opponent's chest, arm, sleeve, or collar. This bind was retained and the arm was not retracted. The 'set' command was an instruction to allow the two front rows to engage and then commence a short-duration sustained push. This condition reflected the law amendment trials introduced globally by the IRB from September 2013.

For all the conditions the coach/referee checked for reasonable distance between packs at set-up and all players simulated competitive scrummaging attempting to adhere to IRB Law 20 (World Rugby, 2015b). All scrums aimed for an "engagement and sustained pressure" type scrum, involving initial engagement phase followed by a ~4 s sustained push.
LH= loose head; TH= tight head.

Table 2. Team subdivision by playing level and average anthropometrics of teams in each group [*]

Category	Competing level	No. of teams	Overall pack mass (across the 8 players) (kg)	Average pack height (individual player) (m)	Average pack age (individual player) (years)
International (I)	Full international forward packs (IRB Tier 1 and 2) or full-time elite professional packs with senior international players	5	887.0 (24.2)	1.90 (0.02)	27 (4)
Elite (E)	Adult male forward packs operating at professional level in the highest leagues of domestic rugby (Level 1 or Level 2) in IRB Tier 1 Unions	6	853.9 (28.0)	1.86 (0.03)	24 (5)
Community (C)	Amateur-level adult male packs from Levels 3 downwards of their respective domestic rugby in IRB Tier 1 Unions	6	815.0 (29.0)	1.82 (0.03)	26 (6)
Women (W)	Adult female teams from the higher levels of the women's game (6 Nations, RFU Premiership, Nations Cup)	4	631.0 (21.1)	1.70 (0.02)	25 (5)
University (U)	Adult male packs (18-21 year-old range) from British Universities & Colleges Sport (BUCS) 1st XV squads	6	818.0 (40.1)	1.86 (0.02)	21 (3)

[*] Measures are reported as mean (SD).

Table 3. Kinematic measures of the front row players during the approach to contact (APRC), across the three different engagement conditions and the five different playing levels. *

Variable\Category		CTPE	CTS	PreBind
Timing				
Time of onset of movement [s]	**ALL** $^{\#}$	-0.28 (0.16) ^{3}	-0.28 (0.20) ^{3}	-0.15 (0.21) ^{1,2}
Interval between the referee's engagement call (i.e. "Engage" or "Set", depending on condition) and the initiation of movement.	**I**	-0.39 (0.19)	-0.31 (0.25)	-0.15 (0.26)
NB. Negative values indicate anticipation of movement with respect to the call.	**E**	-0.27 (0.18)	-0.28 (0.18)	-0.08 (0.18)
	C	-0.26 (0.16)	-0.18 (0.19)	-0.15 (0.16)
	W	-0.29 (0.14)	-0.28 (0.23)	-0.09 (0.30)
	U	-0.23 (0.15)	-0.38 (0.15)	-0.25 (0.19)
Motions and postures				
Distance between front rows [m]	**ALL** $^{\#\dagger}$	0.48 (0.07) ^{3}	0.48 (0.07) ^{3}	0.35 (0.09) ^{1,2}
Average distance between opposing front row players C7 landmarks at the onset of movement.	**I** ^{c}	0.40 (0.07)	0.43 (0.04)	0.32 (0.05)
	E ^{c}	0.46 (0.05)	0.48 (0.05)	0.33 (0.10)
	C $^{e, i, w}$	0.55 (0.07)	0.54 (0.10)	0.40 (0.10)
	W ^{c}	0.45 (0.05)	0.46 (0.06)	0.32 (0.09)
	U	0.48 (0.04)	0.48 (0.06)	0.35 (0.07)
Maximum engagement speed [m/s]	**ALL** $^{\#\dagger}$	2.62 (0.44) ^{3}	2.47 (0.45) ^{3}	2.06 (0.50) ^{1,2}
Maximum value of the sum of the velocities of the two front rows coming together.	**I**	2.45 (0.31)	2.48 (0.45)	1.92 (0.48)
NB. The absolute value of the component of velocity in the direction of scrummaging was considered.	**E**	2.70 (0.44)	2.64 (0.41)	2.12 (0.42)
	C ^{u,w}	2.95 (0.43)	2.70 (0.48)	2.40 (0.56)
	W ^{c}	2.12 (0.22)	2.21 (0.30)	1.80 (0.53)
	U ^{c}	2.57 (0.36)	2.21 (0.37)	1.94 (0.42)
Shoulder-hip height offset at set-up LH players [m]	**ALL** $^{\#\dagger}$	0.02 (0.04) ^{3}	0.03 (0.05) ^{3}	0.05 (0.04) ^{1,2}
Distance between shoulder and hip height along the vertical direction (i.e. "shoulder above hip" position).	**I** $^{e, u, w}$	0.07 (0.05)	0.07 (0.03)	0.08 (0.03)
NB. Positive values mean shoulder higher than hip.	**E** $^{c, i,}$	0.00 (0.03)	-0.01 (0.03)	0.03 (0.05)
	C $^{e, u}$	0.04 (0.03)	0.06 (0.04)	0.07 (0.04)
	W	0.00 (0.03)	0.03 (0.04)	0.06 (0.04)
	U ^{i}	0.00 (0.03)	0.01 (0.03)	0.04 (0.03)
Shoulder-hip height offset at set-up TH players [m]	**ALL** $^{\#}$	0.04 (0.04) ^{2,3}	0.05 (0.05) ^{1,3}	0.07 (0.04) ^{1,2}
	I	0.05 (0.04)	0.05 (0.04)	0.08 (0.03)
	E	0.03 (0.03)	0.04 (0.04)	0.05 (0.04)
	C	0.06 (0.04)	0.08 (0.05)	0.08 (0.04)
	W	0.05 (0.05)	0.07 (0.05)	0.10 (0.03)
	U	0.03 (0.03)	0.04 (0.03)	0.06 (0.04)

* Measures are reported as mean (standard deviation). ALL= all playing standards, I= International, E= Elite, C= Community, W= Women, U= University. Significant main effect ($P<0.05$) between engagement conditions ($^{\#}$) and pairwise comparisons are reported by the following convention: ^{1}= different from CTPE; ^{2}= different from CTS; ^{3}= different from PreBind. Significant main effect ($P<0.05$) between playing levels (†) and pairwise comparisons are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{w}= different from Women; ^{u}= different from University. LH= loose head; TH= tight head.

Table 4. Kinematic and kinetic measures during the engagement phase (ENG), across the three different engagement conditions and the five different playing levels. *

Variable\Category		CTPE	CTS	PreBind
Force				
Peak of total force [kN]	**ALL** [#]	8.4 (2.7) [3]	8.3 (2.4) [3]	6.3 (1.7) [1,2]
Maximum of the force at the interface between front rows during engagement (sum of front row players).	**I**	9.3 (2.8)	9.1 (2.4)	6.3 (1.2)
	E	10.1 (2.9)	8.7 (2.4)	6.3 (2.0)
	C	8.5 (2.7)	8.7 (3.5)	6.6 (2.3)
	W	6.1 (2.0)	7.3 (1.2)	5.9 (1.6)
	U	7.2 (1.9)	7.2 (1.6)	6.1 (1.8)
Loss of total force during the “rebound” [kN]	**ALL** [#]	5.2 (2.1) [3]	5.2 (1.8) [3]	3.6 (1.5) [1,2]
Difference between the max and min value of force in the transition between the initial contact and the sustained push phase. Force traces typically show an initial peak followed by a steep decrease of pushing capability, which has been identified as the “rebound” effect (Cazzola *et al.*, 2015b; Preatoni *et al.*, 2014).	**I**	5.8 (2.4)	5.8 (1.9)	3.1 (1.0)
	E	6.4 (2.1)	4.9 (1.4)	3.4 (1.8)
	C	5.3 (2.7)	6.1 (2.6)	4.7 (1.8)
	W	3.7 (1.4)	4.7 (1.0)	2.8 (1.0)
	U	4.6 (1.4)	4.3 (1.7)	3.4 (1.3)
Accelerations				
Average peak acceleration at cervical level [g]	**ALL** [#]	5.89 (0.75) [3]	5.62 (0.77) [3]	4.85 (0.64) [1,2]
Average of the individual C7 accelerations across the front row players.	**I**	6.28 (0.65)	5.44 (0.96)	4.68 (0.94)
	E	5.80 (0.63)	5.92 (0.44)	5.05 (0.54)
	C	6.32 (0.83)	5.84 (1.15)	5.17 (0.52)
	W	5.41 (0.74)	5.48 (0.91)	4.43 (0.83)
	U	5.59 (0.67)	5.33 (0.34)	4.73 (0.47)
Maximum peak acceleration at cervical level [g]	**ALL** [#]	8.20 (1.10) [3]	7.93 (1.27) [3]	6.80 (1.23) [1,2]
Maximum of the individual C7 accelerations across the front row players.	**I**	8.58 (0.26)	7.63 (2.00)	6.31 (1.58)
	E	7.94 (1.14)	8.35 (1.03)	7.25 (1.21)
	C	9.41 (0.92)	7.81(1.36)	7.26 (1.50)
	W	7.79 (0.71)	8.37 (1.27)	6.27 (1.18)
	U	7.24 (0.60)	7.54 (1.06)	6.59 (0.72)
Motions and postures				
Hip angle range of motion LH players [°]	**ALL** [#]	35 (13) [2]	27 (10) [1]	27 (12)
Maximum hip joint range (max extension – max flexion) across the engagement phase. The hip was defined as the angle between the trunk (segment connecting C7 and sacrum) and the thigh (segment connecting the greater hip and knee, as in (Cazzola *et al.*, 2015b; Preatoni *et al.*, 2014).	**I**	32 (8)	28 (10)	19 (5)
	E	32 (12)	23 (7)	28 (10)
	C	33 (13)	29 (10)	32 (15)
	W	40 (17)	34 (13)	30 (11)
	U	36 (12)	23 (8)	24 (11)
Hip angle range of motion TH players [°]	**ALL** [#]	49 (15) [2,3]	39 (15) [1]	35 (11) [1]
	I	48 (9)	36 (13)	30 (10)
	E	45 (12)	37 (14)	32 (9)
	C	50 (11)	44 (13)	41 (12)
	W	60 (22)	49 (21)	39 (16)
	U	43 (14)	32 (9)	34 (9)
Shoulder vertical excursion LH players [m]	**ALL** [#]	0.20 (0.05) [3]	0.19 (0.05) [3]	0.17 (0.04) [1,2]
Maximum vertical excursion of the shoulder landmark in the sagittal plane (see also Figure 1).	**I**	0.17 (0.06)	0.17 (0.04)	0.16 (0.04)
	E	0.19 (0.07)	0.19 (0.05)	0.17 (0.04)
	C	0.22 (0.05)	0.18 (0.05)	0.18 (0.04)
	W	0.21 (0.04)	0.20 (0.04)	0.15 (0.05)
	U	0.20 (0.04)	0.21 (0.07)	0.17 (0.05)
Shoulder vertical excursion TH players [m]	**ALL** [#]	0.16 (0.04) [3]	0.16 (0.04) [3]	0.14 (0.04) [1,2]
	I	0.14 (0.03)	0.14 (0.04)	0.11 (0.04)
	E	0.17 (0.05)	0.15 (0.03)	0.13 (0.03)

	C	0.17 (0.04)	0.17 (0.06)	0.16 (0.04)
	W	0.15 (0.05)	0.16 (0.03)	0.12 (0.03)
	U	0.17 (0.04)	0.19 (0.05)	0.15 (0.04)
Stability ellipse of LH players centre of mass [m^2]	**ALL** $^{\#}$	0.08 (0.03) ^{2,3}	0.07 (0.02) ^{1,3}	0.05 (0.02) ^{1,2}
Area of the ellipse describing the degree of variability (95% confidence area) in the sagittal plane of the trajectory of the player's centre of mass (see also Figure 1). NB. The larger the area, the more movement is present in the scrum.	**I**	0.08 (0.05)	0.06 (0.02)	0.04 (0.02)
	E	0.08 (0.03)	0.06 (0.02)	0.05 (0.02)
	C	0.08 (0.02)	0.08 (0.02)	0.07 (0.02)
	W	0.09 (0.04)	0.06 (0.03)	0.05 (0.02)
	U	0.08 (0.03)	0.07 (0.03)	0.04 (0.02)
Stability ellipse of TH players centre of mass [m^2]	**ALL** $^{\#,\dagger}$	0.08 (0.03) ^{3}	0.07 (0.03) ^{3}	0.05 (0.02) ^{1,2}
	I ^{c}	0.06 (0.01)	0.06 (0.02)	0.04 (0.01)
	E	0.08 (0.03)	0.06 (0.03)	0.05 (0.02)
	C ^{i}	0.09 (0.03)	0.08 (0.03)	0.05 (0.02)
	W ^{c}	0.07 (0.02)	0.06 (0.02)	0.04 (0.01)
	U	0.08 (0.03)	0.07 (0.03)	0.05 (0.02)

* Measures are reported as mean (standard deviation). ALL= all playing levels, I= International, E= Elite, C= Community, W= Women, U= University. Significant main effect (P<0.05) between engagement conditions ($^{\#}$) and pairwise comparisons are reported by the following convention: ^{1}= different from CTPE; ^{2}= different from CTS; ^{3}= different from PreBind. Significant main effect (P<0.05) between playing levels (†) and pairwise comparisons are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{w}= different from Women; ^{u}= different from University. LH= loose head; TH= tight head.

Table 5. Kinematic and kinetic measures during the sustained push (SPSH), across the three different engagement conditions and the five different playing levels. *

Variable\Category		CTPE	CTS	PreBind
Force				
Average sustained push [kN]	**ALL**	3.6 (1.4)	3.4 (1.4)	3.4 (1.1)
Average value of the force exchanged at the interface between front rows over the sustained push phase (sum of front row players).	**I**	3.7 (0.7)	3.8 (0.7)	4.1 (0.7)
	E	4.4 (1.9)	3.9 (1.5)	3.7 (1.3)
	C	3.8 (1.4)	3.1 (2.0)	2.8 (1.2)
	W	2.6 (0.5)	2.7 (0.2)	3.3 (0.7)
	U	3.1 (1.4)	3.4 (1.5)	3.1 (1.4)
Motions and postures				
Shoulder-hip height offset LH players [m]	**ALL** †	0.01 (0.08)	0.00 (0.07)	0.01 (0.07)
Distance between shoulder and hip height along the vertical direction (i.e. "shoulder above hip" position). NB. Positive values mean shoulder higher than hip.	**I**	0.01 (0.04)	0.03 (0.03)	0.00 (0.06)
	E ^{w,}	-0.02 (0.07)	-0.04 (0.05)	-0.01 (0.05)
	C	0.02 (0.07)	0.03 (0.07)	0.02 (0.07)
	W ^{e,u}	0.09 (0.06)	0.03 (0.08)	0.04 (0.10)
	U ^{w}	-0.04 (0.08)	-0.03 (0.06)	0.00 (0.05)
Shoulder-hip height offset TH players [m]	**ALL** †	0.14 (0.07)	0.14 (0.07)	0.14 (0.07)
	I	0.14 (0.04)	0.13 (0.04)	0.13 (0.04)
	E ^{w,}	0.11 (0.06)	0.09 (0.05)	0.12 (0.07)
	C	0.14 (0.05)	0.17 (0.06)	0.15 (0.07)
	W ^{e,u}	0.20 (0.05)	0.20 (0.08)	0.17 (0.06)
	U ^{w}	0.14 (0.10)	0.12 (0.06)	0.13 (0.09)

* Measures are reported as mean (standard deviation). ALL= all playing levels, I= International, E= Elite, C= Community, W= Women, U= University. Significant main effect (P<0.05) between engagement conditions ($^{\#}$) and pairwise comparisons are reported by the following convention: ^{1}= different from CTPE; ^{2}= different from CTS; ^{3}= different from PreBind. Significant main effect (P<0.05) between playing levels (†) and pairwise comparisons are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{w}= different from Women; ^{u}= different from University. LH= loose head; TH= tight head.

FIGURES

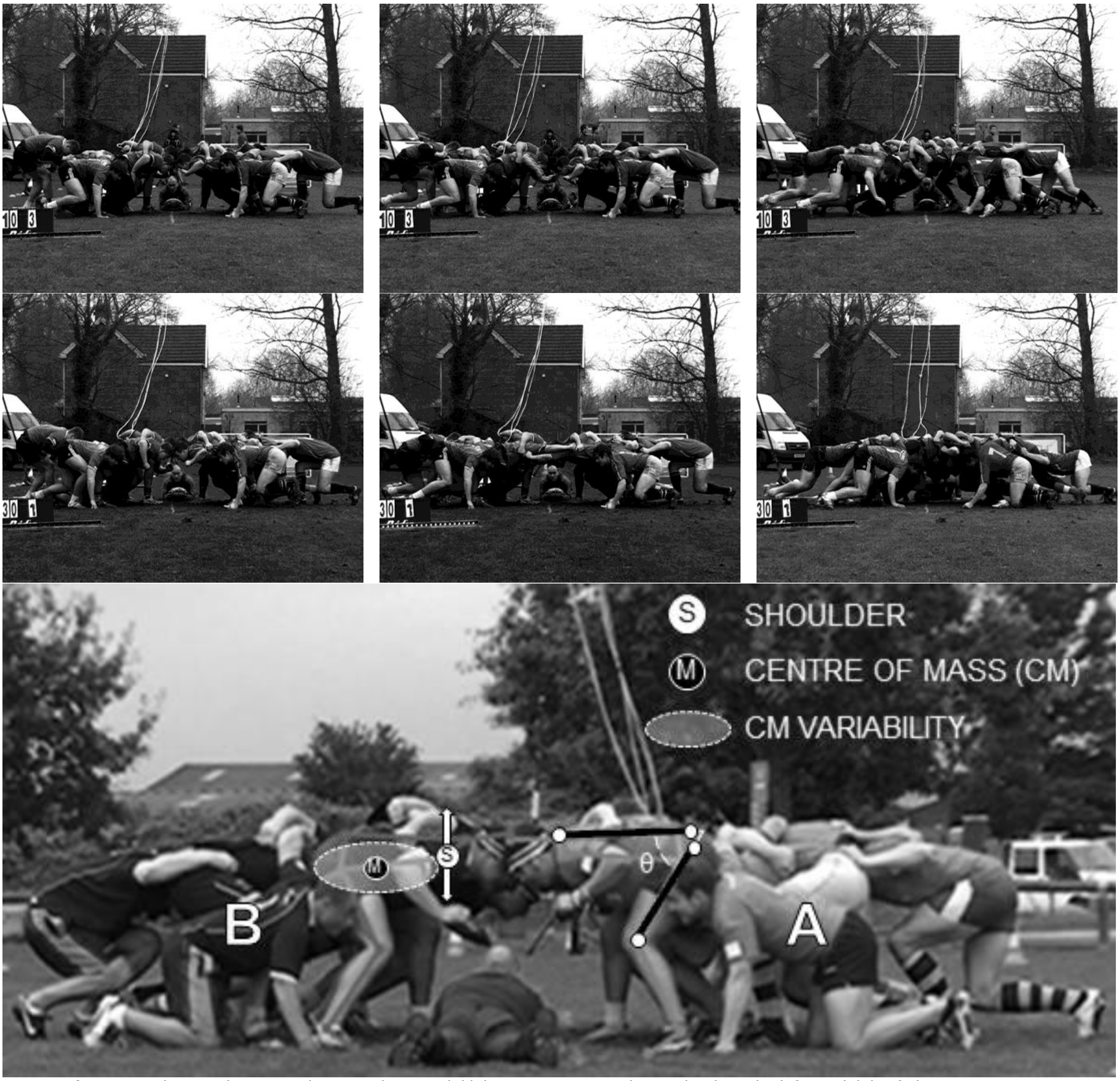

Figure 1. Three subsequent instants (set-up, initial engagement and sustained push, left to right) of the scrummaging procedure in the CTPE (a) and PreBind (b) conditions. (c) Reports an annotated representation of the scrum after the “crouch” call. A is the attacking team and B is the defending one. For clarity of representation some parameters have been graphically reported in either the loose-head prop of team A or the tight-head prop of team B. S= shoulder joint; M= centre of mass of the player; θ= hip angle. The arrows represent the vertical excursion of the shoulder and the shaded area is the confidence ellipse that contains 95% of the points of the trajectory of the centre of mass over the considered interval.